Int J Life Cycle Assess (2013) 18:1686–1697
DOI 10.1007/s11367-012-0509-5

Life cycle sustainability assessment in the context of sustainability science progress (part 2)

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Received: 13 March 2012 / Accepted: 16 September 2012 / Published online: 29 September 2012

Abstract

Purpose In the context of progress of sustainability science, life cycle thinking and, in particular, life cycle sustainability assessment may play a crucial role. Environmental, economic and social implications of the whole supply chain of products, both goods and services, their use and waste management, i.e. their entire life cycle from "cradle to grave" have to be considered to achieve more sustainable production and consumption patterns. Progress toward sustainability requires enhancing the methodologies for integrated assessment and mainstreaming of life cycle thinking from product development to strategic policy support. Life cycle assessment (LCA), life cycle costing (LCC) and social LCA (sLCA) already attempt to cover sustainability pillars, notwithstanding different levels of methodological development. An increasing concern on how to deal with the complexity of sustainability has promoted the development of life cycle sustainability frameworks. As a contribution to the ongoing scientific debate after the Rio+20 conference, this paper aims to present and discuss the state of the art of life cycle sustainability assessment (LCSA), giving recommendations for its further development in line with ontological, epistemological and methodological aspects of sustainability science.

Methods Building on the review about the state of the art of sustainability science and sustainability assessment methods presented in part I, this paper discuss LCA, LCC, sLCA and LCSA against ontological, epistemological and methodological aspects of ongoing scientific debate on sustainability. Strengths and weaknesses of existing life cycle-based methodologies and methods are presented. Besides, existing frameworks for LCSA are evaluated against the criteria defined in part I in order to highlight coherence with sustainability science progress and to support better integration and mainstreaming of sustainability concepts.

Conclusions and outlook LCSA represents a promising approach for developing a transparent, robust and comprehensive assessment. Nevertheless, the ongoing developments should be in line with the most advanced scientific discussion on sustainability science, attempting to bridge the gaps between the current methods and methodologies for sustainability assessment. LCSA should develop so as to be hierarchically different from LCA, LCC and sLCA. It should represent the holistic approach which integrates (and not substitutes) the reductionist approach of the single part of the analysis. This implies maintaining the balance between analytical and descriptive approaches towards a goal and solution-oriented decision support methodology.

Keywords Life cycle sustainability assessment · Science–policy interface · Stakeholder involvement · Sustainability science · Value choices

Responsible editor: Thomas Swarr

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1 Introduction

The dynamic evolution and the complexity of the challenges posed by sustainable development (SD) are hardly manageable in the context of classical disciplines and science. Therefore, over a decade ago, a new discipline called "Sustainability Science" (SS) has emerged. SS could be defined as a "solution-oriented discipline that studies the complex relationship between nature and humankind, conciliating the scientific and social paradigms which are mutually influenced- and covering multi temporal and spatial scales" (Sala et al. 2012a). The scientific paradigm, like in any other discipline, is characterised by its own ontology, epistemology and methodology, whereas the social paradigm is defined by the specific socioeconomic and cultural context where the sustainability problem may emerge and find a solution. In the part I of this study (Sala et al. 2012a), we analysed and discussed the features of the SS scientific paradigm, reporting key issues of the current debate and proposing a conceptual framework for SS.

Because SS is a solution-oriented discipline, the core scientific questions are related on how properly assessing and proactively enhancing sustainability. A plethora of sustainability assessment (SA) methods and methodologies exist, which have been reviewed in Sala et al. (2012a) in order to explore their features and peculiarities as SS methods. Due to its systemic approach, life cycle thinking (LCT) is considered a valuable support in sustainability evaluations, and evidence of this is given by the numerous environmental policies at European level for which LCT represents the backbone (e.g. CEC 2004, 2005, 2008, 2011). Actually, life cycle approaches and in particular the life cycle assessment (LCA) methodology are inherently rooted into SS, at the conceptual level. In fact, LCA distinguishes itself mainly for the following characteristics: (1) the system thinking, i.e. the capability of understanding and addressing a system by analysing the linkages and interactions between the elements that compose the entirety of the system; (2) the interdisciplinary approach, whose most evident example is given in the impact assessment phase. Such characteristics show that LCA already fulfils one of the main requirements of sustainability assessment methods and approaches emerged from the meta-review conducted in part I (Sala et al. 2012a). However, we found that LCA and other life cycle-based methods (e.g. environmental life cycle costing and social life cycle assessment) are not considered as reference methods for SA.

Recent developments in LCA led to the proposal of frameworks for a life cycle-based sustainability assessment. Presently, two basic approaches can be identified: a life cycle sustainability assessment (LCSA assessment) proposed by Kloepffer (2008) and a life cycle sustainability analysis (LCSA analysis) proposed by Guinée et al. (2011). They differ substantially in terms of conceptual structure and modelling principles, even if both share the life cycle structure and some of the methods, such as environmental life cycle costing (eLCC) and social life cycle assessment (sLCA); however, in the review papers analysed in Sala et al. (2012a), the vision of a framework for LCSA was neglected. Despite the relatively young history of LCSA,[1] such a limited recognition of the role of the life cycle-based methods needs to be further explored and analysed.

Considering the developments that have recently occurred in the LCSA field, the recent scientific debate on SS and related SA methods presented in part I, this paper is aimed at contributing to the ongoing debate on sustainability in the year of Rio+20 conference by means of discussing the LCSA in the light of SS. More in detail, this paper discusses the level of mainstreaming of sustainability into the LCA, eLCC and sLCA methods. Then, building on the conceptual framework for SS defined in part I (Sala et al. 2012a), the current LCSA frameworks have been analysed against key SS requirements in terms of ontological, epistemological and methodological aspects, which have been identified in part I (Sala et al. 2012b), namely value choice, completeness of scope, geographical and temporal scale of the assessment, strategicity, integratedness, applicability, scientific robustness and participation of stakeholders. Finally, areas of potential improvement of LCSA have been identified, together with recommendations for its further development coherent with the ontological, epistemological and methodological progress of SS.

2 LCA and sustainability

LCA has been continuously developing over the past 30 years, with notable improvements at the modelling level both in the inventory and impact assessment. Nowadays, it is successfully used in the private sector, e.g. for continuous environmental improvements of products; internal strategic decision support; evaluating risks and opportunities along the supply chain; communication on strategic aspects with stakeholders at company and association level; communication with customers on products, e.g. via environmental product declarations and carbon labels, just to mention a few. Over the years, a shift has occurred from merely energy and environmental analysis to more comprehensive assessments, which include economic and social aspects (Benoît and Mazijn 2009; Swarr et al. 2011). LCA, eLCC and sLCA

[1] First approaches date back to 1998 (Andersson et al. 1998).

already attempt to cover sustainability pillars, notwithstanding their different degree of maturity. In fact, the recent development of the social methodology, coupled with the more established eLCC and LCA, served as the basis for first applications (Ciroth and Franze 2011; Franze and Ciroth 2011; Valdivia et al. 2011) of the LCSA framework elaborated by Kloepffer (2008).

If we briefly run through the history of LCA and we analyse how sustainability has been dealt with, surprisingly we find few approaches and few articles concerning this aspect. As far as we know, the first attempts date back to 1998. Andersson et al. (1998) examined the feasibility of incorporating the concept of sustainability principles into each phase of LCA. Four socio-ecological principles were identified:

- Substances from the lithosphere must not systematically accumulate in the ecosphere (i.e. the use of fossil fuels and mining must be radically decreased);
- Society-produced substances must not systematically accumulate in the ecosphere;
- The physical conditions for production and diversity within the ecosphere must not systematically deteriorate; and
- The use of resources must be efficient and must meet human needs

Subsequently, the Natural Step approach was proposed (Upham 2000; Ny et al. 2006), aimed at overcoming what the authors considered a limitation in LCA, that is, its lack of sustainability perspective. Quoting the authors, "LCAs often lack a sustainability perspective and bring about difficult trade-offs between specificity and depth on the one hand, and comprehension and applicability on the other" (Ny et al. 2006, p. 62). The backcasting approach from basic principles of sustainability was thus elaborated, resulting in a more complete method than present LCA, from a sustainability point of view. The main critique addressed to LCA is that, despite its system approach, in practice it is still based on a reductionist approach. In fact, in order to make the method applicable in the day-by-day, simple in its application but methodologically robust, due simplifications have been introduced. The steady-state type of modelling and the linear relationships used to specify processes in LCA implicitly define (unrealistic) conditions typical of a ceteris paribus assumption (Lundie et al. 2007), which, assuming away any interference from the system, works under the hypothesis of isolation. Thus, "no other technologies will change; no market adaptations other than supply–demand matching for the functional unit will take place" (Lundie et al. 2007, p. 78). Mechanisms and relationships within the system are disregarded and this assumption implies the inability to understand and describe emergent phenomena, according to which the complex systems show characteristics and behaviour that cannot be understood from the analysis of their main parts.

All these limitations have been largely debated by the scientific community (Andersson et al. 1998; Hunkeler and Rebitzer 2005; Reap et al. 2008a, b; Jeswani et al. 2010; Finnveden et al. 2009; Sala et al. 2012a) and the question whether or not LCA can be considered suitable for sustainability evaluations has arisen.

Besides the approaches identified above, which are mainly oriented towards the development of conceptual and methodological frameworks for addressing sustainability with a life cycle-based approach, several methodological developments have occurred in the last years in order to guarantee that LCA fully covers the "environment" pillar with an integrated and comprehensive assessment.

In the next section, we briefly present these recent methodological developments, without claiming to be complete and detailed, as such type of analysis is out of the scope of the present paper and it is properly covered in recent publications (e.g. Bare 2010; Finnveden et al. 2009; Guinée et al. 2011; Reap et al. 2008a, 2000b; Zamagni et al. 2012a). The purpose is to highlight those approaches which would support a shift from LCA to LCSA and for which several methods have been developing.

2.1 Life cycle inventory and impact assessment

The scientific literature (e.g. Heijungs et al. 2010; Graedel and van der Voet 2010) clearly points out that the achievement of ambitious goals such as those mentioned in the previous section requires a breakthrough both at conceptual and at modelling level. At conceptual level, recent research thrusts are going towards a reconciliation of bottom-up and top-down modelling, such as LCA and integrated assessment models, respectively. Creutzig et al. (2012, p. 6) nicely point out that an "improved exchange between bottom-up and top-down communities is a precondition for better understanding benefits and costs of bioenergy deployment for climate change mitigation". In fact, this integration would allow addressing some important challenges in the research community for achieving a comprehensive assessment such as: increase level of detail across temporal and spatial scales, market resolution and trade-offs; close research gap in consequential assessments; increase transparency on uncertainty and underlying assumptions.

As far as the modelling is concerned, for the inventory phase, more sophisticated methods have been developed at a growing rate in the last years. Consequential LCA (cLCA), hybrid approaches, temporal differentiation and adding optimization strategies through linear and nonlinear programming are some representative examples of the need to further advance the present LCA. Further research activities are necessary to fully develop them (see for example recent

reviews by Finnveden et al. 2009; Zamagni et al. 2012a) but they represent attempts to move LCA in those directions considered relevant for SS. In fact, hybrid approaches provide their usefulness in making LCA more complete in terms of system definition, while cLCA offers the conceptual framework for including mechanisms (presently those at market level) into the analysis and thus introducing the linkages and the causality chain pointed out as fundamental in any sustainability evaluations. The biofuel case provides a nice example of the type of linkages to be taken into account. As described in Heijungs et al. (2009) and Guinée et al. (2009), the introduction of a new energy product into the market, such as bioethanol, causes changes in price and in volume of related commodities. The increased amount of corn required for producing bioethanol causes a reduced amount of corn available for food and also of land use for producing substituting commodities, such as wheat. The price of both wheat and corn will increase, causing many effects also at societal level as in some regions there will not be enough cereals for everybody and this might cause civil conflicts. As can be understood from this simple example, "there always is a close correspondence between economy and technosphere, with production and consumption having utility, at the society side, and having physical requirements and effects" (Guinée et al. 2009, p. 59).

At the level of impact assessment, in the last decade, there was a thriving development of the impact assessment modelling (EC-JRC 2011; Hauschild et al. 2012; Sala et al. 2012b). In this setting, the Joint Research Centre of the European Commission has launched the International Reference Life Cycle Data System (ILCD) to develop technical guidance that complements the ISO Standards for LCA and provides the basis for greater consistency and quality of life cycle data, methods and LCA studies. Inherent to this goal is the development of recommendations of best practice characterization framework, models and factors. The handbook provides guidelines to methods to assess emissions into air, water and soil, as well as the natural resources consumed in terms of their contributions to different impacts on human health, natural environment and availability of resources. Those guidelines come from a comprehensive process of selection of methods based on a set of scientific and stakeholder acceptance criteria (Hauschild et al. 2012) and involving experts, advisory groups and the public. In this "from science to decision support" process, a number of critical issues and challenges for LCIA emerged both in terms of comprehensiveness of the impact coverage and of the further mainstreaming of the sustainability principles.

The main gaps for covering the environmental dimension of sustainability concern the completeness of scope in terms of:

(a) Number of substances/flows covered by existing methods, e.g. the number of chemical substances in the ecotoxicity and human toxicity models covers a relatively small percentage of the overall existing chemicals (around 3,000 have characterization factors compared to 90,000 chemicals registered in the EU for the REACH directive (ECHA 2012), or comprehensive coverage of resources (not only minerals and fossil fuels but also critical raw materials, not only abiotic but also biotic and not only mineral stock but also anthropogenic) (Klinglmaier et al. 2012)).
(b) Target of impacts: e.g. for ecotoxicity, the models mainly cover freshwater ecotoxicity while epigean and hypogean terrestrial ecotoxicity or marine ecotoxicity are still less developed. Concerning other impact on ecosystems, such as the biodiversity loss due to different drivers (land use, pollution, etc.), a recent review (Curran et al. 2011) has identified serious conceptual shortcomings in the way models in LCA are constructed. The major issues are related to the fact that functional and structural attributes of biodiversity are largely neglected whereas the focus is mainly on compositional aspects of biodiversity, as changes in species richness.
(c) Number of impact categories: e.g. to tackle emerging issues, like noise, desertification, accidents and genetically modified organisms.
(d) Cause–effect modelling: completeness and robustness of endpoint methods are not entirely satisfactory at their current development level. Indicators and factors are presented at both midpoint and endpoint in a consistent framework, but the latter is in many cases still too immature to be recommended for use (EC-JRC 2011).

At the level of normalisation, a relevant role may be played by the choice of the reference values. Ideally, integrating sustainability goals may require not only the normalisation of impact assessment results in terms of overall emissions at a certain scale (country, continent and global) but also the fostering of sustainability, through the use of normalisation factors in terms of what could be considered acceptable (e.g. in line with the planetary boundaries charted by Rockström et al. (2009)). This may also be valid for the weighting step, in which for example the distance-to-target approaches already attempted to combine policy target with the results of the assessment (Weiss et al. 2007). Both at the normalisation and the weighting step, the task is very challenging and complex but crucial for moving from environmental assessment to sustainability assessment, granting more focus on the Earth's carrying capacity and planetary boundaries.

Overall, addressing complexities of the real world into a life cycle-based framework requires an increasing sophistication in the computational structure, borrowing techniques

from other disciplinary fields such as urban planning, geography and many others. These techniques could include for example machine learning algorithms, geostatistics, remote sensing, geographical information systems, biophysically based models, linear programming and constraint programming, Bayesian network (Marvuglia 2012), agent-based modelling (e.g. Bichraoui and Halog 2012), system dynamics (e.g. Stasinopoulos et al. 2012) and general/partial equilibrium models. They can provide a useful support for land use modelling and spatial differentiation, to mention just a few examples, besides processing a massive amount of diverse types of data.

2.2 LCA and stakeholder's involvement

Even if the role of collaborations and partnerships within and across different stakeholder groups for sustainability assessment has been widely recognised (e.g. Blackstock et al. 2007; Talwar et al. 2011), stakeholder involvement in LCA is a less explored field. Theoretically, in the goal and scope phase of the methodology, the interested parties should be involved in order to better define the decision context and the purpose of the study, but in practice an LCA is carried out for one actor only. A stakeholder-based approach has been proposed by Thabrew et al. (2009), aiming at supporting the decision making process by means of the following: facilitating the interaction of stakeholders at all stages; mapping those potentially affected by the environmental, economic and social aspects of the proposed project; and by communicating to stakeholders the implications of the project in a clear and transparent way.

Approaches to stakeholders' involvement should be further developed, and the logic of life cycle thinking has proved its utility also in this context, by making available the conceptual framework for providing stakeholders with "a holistic view of issues that they otherwise may not have" (Thabrew et al. 2009, p. 68). Interesting examples of the involvement of business' stakeholders in the context of LCA were already developed (e.g. the supply chain collaboration model of Nakano and Hirao 2011) but, so far, a community-wide participation is not structured. In a community-wide involvement, stakeholders will not only serve as audience but as active, informed and responsible parties in the decision making process.

2.3 Economic and social pillars: LCC and sLCA

In the scientific literature, there are plenty of examples of methods and models which attempt to account for the economic dimension in a sustainability evaluation, including externalities (e.g. Friedrich 2011).

In LCA, the economic dimension is mainly restricted to the business point of view, using the concept of life cycle costs and the methodology of eLCC (Swarr et al. 2011). However, even if the eLCC framework mirrors the LCA procedure, it differs from LCA, not only in terminology but also in content. The relevance of eLCC in SA has been debated in literature and even questioned (Jørgensen et al. 2010) for two main reasons: firstly, by focusing mainly on the costs for the individual, it fails to take into account the broad (global) perspective inherent to sustainability. Secondly, by addressing monetary costs, it fails to consider the different capitals relevant to sustainability. The question has been partly raised also by Schau et al. (2011), who point out that the contribution of eLCC in addressing the economic dimension of SD should be further investigated, together with the aspects of data access and availability. Moreover, it has been highlighted (Settanni 2008) that the current practice of combining separate environmental and economic analysis does not facilitate synergies among LCA and other methods such as eLCC and supply chain management. For this reason, research lines are proposed that go in the direction of developing a formalised computational structure of eLCC that could help in overcoming some methodological and implementation-related inconsistencies that may arise when using eLCC in environmental management and especially in combination with LCA.

With respect to LCC, sLCA is at an earlier stage of development. The recently published guidelines on sLCA (Benoît and Mazijn 2009) condense the knowledge in the field and present a backbone for the evaluation of the social aspects. Still more research is necessary, both at the methodological and practical level, addressing at least the following aspects: (1) analysis of the relevant decision contexts for sLCA (which question to answer, which stakeholders to address), (2) development of databases, (3) definition of impact categories and (4) case studies.

Case studies are fundamental in order to increase knowledge and practice, contributing towards an acceleration of the methodology development. In some calls for proposal of the Seventh Framework Programme,[2] projects are required to perform LCA, eLCC and sLCA of the specific technological applications object of the call. This requirement represents an opportunity to further improve and fine tune the methodologies and poses the basis for a better integration/combination within the LCSA framework.

[2] The Seventh Framework Program is a funding programme created by the European Union in order to support research in the European Research Area. Started in 2007, the funding will run until 2013 and it is also designed to respond to Europe's employment needs, competitiveness and quality of life.

3 From reductionism toward holism: LCSA

The developments discussed above highlight that, even if the boundaries of the assessment have been dramatically broadened to include the economic and social dimensions, present LCA does not have all the capabilities to properly take into account all the dynamics within such an expanded system. An attempt to face this challenge, which represents the first proposal of a more comprehensive life cycle-based assessment towards sustainability, is represented by the LCSA assessment framework developed by Kloepffer (2008), and recently updated by Valdivia et al. (2011), according to which LCSA = LCA + eLCC + sLCA. The three methods (LCA, eLCC and sLCA) still work in isolation as they are applied separately, under the requirement of keeping the same system boundary, without taking the mutual relations into account, and this attitude prevents "the observer from comprehending the whole of the system itself" (Osorio et al. 2009). A step forward in the methodological development is necessary, in order to identify and evaluate the interrelations or linkages (Graedel and van der Voet 2010) because the system itself "cannot be grasped just by knowing the independent features of their components separately. Therefore, the focus of analysis is not the properties of the parts, but the interactions that occur between them" (Osorio et al. 2009, p. 51).

Despite these limitations, which are mainly due to the limited knowledge at scientific level about mechanisms and their modelling, a value added of this framework is given by the possibility to jointly evaluate the results of the three assessments, without any compensation and/or substitution among the three pillars but adopting a strong sustainability perspective. However, if on one hand this represents the strength of the approach, on the other hand the interpretation of the results, thus their use in the decision context at hand is left to the final user of the study. In this way, the usefulness of the analysis and its effectiveness are strongly limited, with the risk of losing the credibility and reliability gained by the life cycle methods in its relatively young but scientifically robust history. Approaches to ease the interpretation of the results of such an assessment are starting to be proposed (e.g. Finkbeiner et al. 2010), but further developments are still needed. Moreover, the methods proposed need to be adapted and developed in order to accommodate the normative aspects of the analysis, namely the values and principles which inevitably and unavoidably are brought into the analysis.

A different perspective and vision of what a SA should entail is embedded into the LCSA analysis framework proposed by Guinée et al. (2011). The authors define LCSA (analysis) as an integrated framework for the analysis, able to deal with the complexity and the requirements of sustainability science, which are defined in detail in Sala et al. (2012a).

Even if the two frameworks are both shortened into LCSA, the difference between the "assessment" in one case and the "analysis" in the other is not merely formal but purely substantial since it refers to two different concepts. In fact, sticking to ISO, the word "life cycle assessment" is used mainly to denote LCA at product level, and this is the terminology commonly adopted by all practitioners in this field. The word life cycle analysis is used mainly to define a methodology that goes beyond LCA as defined in ISO. Thus "analysis" refers to the result of an innovation process, like the one which led to the development of the LCSA (analysis) framework (Zamagni et al. 2009).

This LCSA (analysis) framework is able to accommodate knowledge from different disciplines relevant to sustainability and to better link questions to models of analysis towards transdisciplinarity. Moreover, it is characterised by the following aspects, among others:

- It includes both empirical knowledge and normative positions. Following the logic of post-normal science (Funtowicz and Ravetz 1993), the two categories of facts and values cannot be realistically separated. For this reason, the LCSA (analysis) framework merges inventory analysis and impact assessment into one modelling phase, which represents the interdisciplinary integration between and within the different domains relevant to sustainability.
- It recognises that a scientifically based sustainability analysis necessarily involves assumptions, scenarios and uncertainties. The task is not so much to decrease the non-factual content of a sustainability analysis, nor to hide it, but to explicitly incorporate it by adding elements such as uncertainty analyses and discursive procedures (Heijungs et al. 2009).
- It addresses sustainability problems at all levels, from micro- (product) to macro- (economy-wide) level

LCSA (analysis) is a conceptual framework, which needs to be made operational. Most of the present developments in LCA fit into the framework, and a plethora of other methods and tools have already been identified as potentially useful (Jeswani et al. 2010). However, before any choice of methodologies and methods is made, it is necessary to investigate the extent to which the main characteristics and principles of sustainability are taken into account, what is still lacking and what is needed to develop a robust LCSA framework.

3.1 Sustainability science principles into LCSA

In Sala et al. (2012a), we proposed a list of criteria against which the different methodologies and methods for SA could be evaluated and further developed. These criteria

are built for covering ontological, epistemological and methodological aspects of a SA based on the principles of SS. More in detail, they refer to the capability of addressing different capitals, values and goals at ontology level. In terms of epistemology, focus is on collaboration among different disciplines in order to promote the shift from an academic, monodisciplinary and predictive mode of science to a transdisciplinary, participative, uncertain and explorative approach. Finally, at the methodological level, it is necessary to develop different methods capable of modelling different impacts on different capitals, address uncertainties and involve stakeholders in a more structured and participatory way and build scenarios. These concepts have been translated into eight criteria, namely value choice, completeness of scope, geographical and temporal scale of the assessment, strategicity, integratedness, applicability, scientific robustness and participation of stakeholders (Sala et al. 2012a).

Capitalising on the current debate in sustainability science and on the meta review on SA methods (Sala et al. 2012a), the analysis of the main advancements in LCA, eLCC, sLCA and of both LCSA frameworks, we have analysed the two LCSA frameworks against the set of criteria listed above, in order to understand what it is still necessary—in terms of research needs—to develop a sound and robust approach to sustainability assessment.

For each criterion listed in the first column of the table, a number of sub-criteria are identified and discussed in Table 1 for the two LCSA frameworks ((Kloepffer 2008)—LCSA assessment; (Guinée et al. 2011)—LCSA analysis).

The results of the analysis show that most of the characteristics entailed by SS are already embedded into both frameworks, but with important differences among them, as pointed out in the table. More in detail:

– The LCSA (analysis) framework, building on the knowledge matured in the LCA field and in the broader field of industrial ecology, expands the LCSA (assessment) framework, toward an increased comprehensiveness and completeness of the assessment.
– Even if the life cycle approach in principle is coherent with a non-reductionist approach, in practice the LCSA (assessment) framework combines several reductionist methodologies and approaches in order to cover more areas of investigation. From this point of view, it fails to take into account one of the main characteristics of SS. On the other hand, the LCSA (analysis) framework, being an integrated framework, provides the conceptual structure for overcoming the limitation highlighted above. In this respect, the main role is played by the mechanisms introduced into the analysis whose modelling still needs to be fully developed. As pointed out by Osorio et al. (2009, p. 51), from a methodological point of view, "the most fundamental task is not only to know the elements of the system and their relationships, but to understand the dynamics of those relationships both inside the system and outside it, in its relation to the environment and to other systems with which it interacts".
– The LCSA (assessment) framework has been conceived for applications at the product levels, in line with the applications of the three methods LCA, LCC and sLCA (e.g. Ciroth and Franze 2011; Schau et al. 2011; Valdivia et al. 2011), and adopting due simplifications in modelling, as described in Section 2. Decision makers can then use product specific information for different purposes. However, when political consequences are derived from life cycle results, or political decisions affect life cycle studies, the effects at other scales of the analysis than the product one need to be considered, and thus the simplifications usually adopted become tight. In fact, even if the outcome may be that the micro-level questions are essential in the end, macro-level questions may help in better shaping micro-level questions, by bringing focus to the relevance of the micro-level. Moreover, there is the question of emergent phenomena and properties, according to which the system at macro-level might show characteristics and behaviour we could not understand from the observation and analysis of its main parts, at micro-level (Zamagni et al. 2012b). Many applications in the LCA field are going into this direction, applying more sophisticated methods such as the cLCA (see the case of biofuels, as described in Reinhard and Zah 2009) but the LCSA (assessment) framework does not have the capability (from the conceptual and computational point of view) of addressing such types of analysis, while the LCSA (analysis) framework has the capabilities to address sustainability problems at all levels, as described in Section 3. However, many efforts are still necessary to understand how to link the different levels, i.e. how many decisions at the micro-level work out at the macro-level, for total society and vice versa.

Besides differences, the two frameworks have commonalities regarding the lack of a structured approach to the involvement of stakeholders. A life cycle-based method for SA could benefit from the experience gained in the field of environmental impact assessment (in which the participatory process is governed by precise rules) and couple this with life cycle thinking.

Another shared weakness, even if further amplified in the LCSA (analysis) framework, is related to data availability and robustness. The recent initiatives of the International Reference Life Cycle Data Network (EC-JRC 2012) are

Table 1 LCSA frameworks evaluated against the key criteria for sustainability assessment methodologies as in Sala et al. 2012a

Key criteria for sustainability assessment methodologies according to Sala et al. 2012a	LCSA (assessment) framework LCSA = LCA + LCC + sLCA Kloepffer's framework (2008)	LCSA (analysis) framework Transdisciplinary integrated frameworks of models (Guinée et al. 2011)
Ontology–epistemology		
Value choices	Values enter into the frameworks in several parts:	
• Values underpinning the assessment are explicitly mentioned	- Principles which inspire the approach. In this case, a strong sustainability perspective is adopted in both cases.	
	- Value judgments in the weighting step. Even if this step is not recommended by the ISO procedure, weighting is unavoidable and done in practice in many cases. Recent developments in the field are summarise in the recent EC-JRC report by Huppes and van Oers 2011	
	- Clarity on the ethical issues underpinning LCSA is a fundamental for its broad application and acceptance. For this reason, a clear need in both frameworks is to "specify how main ethical positions may be covered in practical indicators and weighting procedures" (Guinée et al. 2009).	
Completeness of scope		
• All dimensions of sustainability are assessed (vs. one dimension of sustainability) and key topics addressed	Both frameworks are complete in terms of sustainability dimensions covered (environmental, economic and social). The relevance of LCC in representing the economic dimension in a sustainability assessment has been questioned, since it is considered to be representative mainly for the industrial context, while sustainability entails various and global contexts which goes beyond the single product/system. So far, within each pillar and each related LCA-based approach, the enhancement of the comprehensiveness of the assessment is one of the goals, not yet fully achieved.	
• Limit of the resources and carrying capacity of the earth system	The state of the art in LCIA shows that presently the life cycle methods do not have capability for addressing such issues, a part from some impact assessment methods, dealing with the concept of critical load (e.g. Seppälä et al. 2006). Furthermore, the modelling of impact assessment at the endpoint level, where concepts such as vulnerability and resilience would be better addressed, is still in an infant stage.	
• Vulnerability • Resilience	Concerning the approach to the "limit", so far distance to target has already attempt to identify "target" to be achieved but those methods has been dealing almost exclusively with "policy defined target"	
• Indirect effects	Covered by both, since this characteristic is inherent to the life cycle approach.	
• Deal with nonlinearities and dynamic features	Linear and steady-state methods, in which time is a parameter outside the model. First approaches have been recently proposed (e.g. Levasseur et al. 2010). Future-orientated assessment is addressed by means of the support of scenario analysis (Höjer et al. 2008)	Dynamics and nonlinearities are considered in the framework, in order to take into accounts mechanisms and interrelations within the studied system. Several options have been identified, for the different levels of analysis (micro, meso and macro)
• Encompass system-wide analysis	Focus mainly at product level.	It encompasses different scales of analysis, from micro-level (product) to meso (basket of products, sectors) and macro-(economy-wide) level, with not a clear distinction among them.
Geographical and temporal scale of the assessment		
• Regionalized approaches • Local issues (for some impact categories local impact may be due to the local context) • Temporal aspects	Traditionally, LCA has been applied in a site-independent manner. In the context of life cycle impact assessment (LCIA), site-dependent characterization factors have been calculated for different impact categories, including for acidification and eutrophication (Seppälä et al. 2006; Gallego et al. 2010), photochemical ozone formation (van Zelm et al. 2008), ecotoxicity and human toxicity (e.g. Wegener Sleeswijk and Heijungs 2010). Temporal issues still in infant stage.	The different levels of scales and the combined/integrated use of different methods into the framework in principle would allow taking spatio-temporal aspects into account.
Strategicity		
• Clear definition of the decision context	The relevance of the decision context is highlighted in the goal and scope phase. Recently, the ILCD Handbook (EC-JRC 2010) further strengthened this concept by means of the distinction of three different decision contexts (A, B, C). They differ in terms of: main types of questions that are addressed with LCA studies;	Strong emphasis on the relevance of "framing the question", i.e. the definition of the question at hand, as it affects the choice of the models to be applied, among others. Detailed description of what the process of framing the question entails has been discussed (Zamagni et al. 2009).

Table 1 (continued)

Key criteria for sustainability assessment methodologies according to Sala et al. 2012a	LCSA (assessment) framework LCSA = LCA + LCC + sLCA Kloepffer's framework (2008)	LCSA (analysis) framework Transdisciplinary integrated frameworks of models (Guinée et al. 2011)
	the intended audience; modelling adopted (attributional vs consequential); approaches to multi-functionality.	
• Assess alternative scenarios (vs. status quo assessment); support scenario development	The assessment of different scenarios is already a practice (in goal and scope the elements relevant for scenario analysis are defined, while their modelling is done in the inventory and impact assessment steps). However, they pose several problems for two main reasons: - They deal with the future that is uncertain by definition. - They involve expertise in different disciplines. Approaches to support scenario development have been discussed (see for example Weidema et al. 2003) but we are still far from a proper systematisation of the approach.	Scenario development and analysis is a building block of the LCSA framework. In fact, the consequences analysed for decision support may extend far beyond the next future. Scenarios in LCSA provide a way to model the mechanisms (cultural, economic, physical, etc.) and relations within the system. This can be done exogenously (scenarios modelled in other domains) or endogenously (at the level of modelling). Detailed research lines have been identified in Guinée et al. (2009).
• Consider a holistic view of the issues, including upstream and downstream consequences (vs. analysis limited to one or two obvious phases)	A holistic and systemic view is shared by both frameworks, according to the life cycle approach, while the degree to which the chain of consequences is taken into account varies. In 1, presently, only technological, environmental and some market mechanisms (consequential approach) are included into the analysis while theoretically 2 considers physical, micro- and macro-economic, cultural, institutional relations.	
Methodology		
Integratedness:		
• Deal with linkages and mechanisms	The framework combines the three pillars but does not really integrate horizontally and vertically the assessment. Interlinkages are missing. This approach maintains high level of comparability among studies.	It is an integrated framework of models, able to accommodate knowledge from different disciplines relevant to sustainability and to better link questions to models of analysis.
Applicability/comparability:		
• Data scarcity • Comparability • Transparency	Data availability and robustness is a key aspect in 1, which has been debating since time. Several approaches and solutions have been proposed, with focus also on specific sectors (e.g. the chemical one) and more recently by the European Platform on LCA (EC-JRC 2012) with the initiatives of the ILCD. The development of the ILCD database and data network is intended to provide the access to reliable and fully documented LCA data, in order to improve the robustness and comparability of the studies. With S-LCA we are still a step backward. Besides the problem of availability, also the reliability is under discussion. Approaches to sector and country specific data are under development (see for example the Hotspot database, Benoît et al. 2010).	The question of applicability and comparability is even more demanding in 2, due to the complexities introduced into the analysis. As several methods and models will be used into the framework, it is of paramount importance to understand the data exchange among them in terms of content, format, semantic, etc. The same critical aspects of 1 apply also in 2 with regard to social and economic aspects. In both cases, a structured approach to data and meta-data documentation is a condition sine qua non to guarantee transparency of the analysis.
Scientific robustness		
• Dealing with variability and uncertainties	Approaches to uncertainty analyses have been developed since time in LCA, even if they are not always applied in LCAs studies. Approaches to parameter uncertainty are the most addressed ones, while model and scenario uncertainty are less investigated and still developments are necessary.	In 2, due to the many methods, models, assumptions, choices and data involved into the analysis, uncertainties are a critical aspect. Practical uncertainty analysis methodology for LCSA should be developed, starting from the achievements in the LCA field, in order to provide a better basis for interpreting results of studies.
Participation of stakeholders		
• Dealing with stakeholders	The importance of the issue is acknowledged in both the frameworks but it not yet fully addressed.	

aimed at providing reliable, robust and fully documented life cycle inventory datasets, in order to increase the comparability of the studies. Much more critical is the situation for data representing social aspects of concern (for example those related to equal opportunities/discrimination, corruption and freedom of association) because besides the problem of availability the question of reliability should also be addressed. However, setting a data demanding framework may steer the efforts in the near future towards better and wider data collection.

Overall, the LCSA (analysis) framework characterises itself as an evolution of the present way in which sustainability evaluations are dealt with, and it already includes many aspects entailed by SS at ontological, epistemological and methodological level. However, LCSA (analysis) is elaborated only at the conceptual level, and needs to be made operational. Clearly there is not a one-size-fits-all solution to integrating different life cycle-based methods because it is the question at hand and thus the purpose of the study which guides decision making. However, even when methodologies and methods are identified, elements for integration and/or combination should be critically evaluated, according to defined criteria which we think should at least take into account the following characteristics (Zamagni et al. 2009):

– Level of answers (product, meso, economy-wide);
– Thematic coverage (for example, within the environmental domain: biodiversity, resources, energy, climate change, etc.);
– Scientific background and principles. Main principles governing the models (e.g. thermodynamic laws);
– Geographical and temporal coverage;
– Analytical technique, i.e. the kind of model used (accounting system vs. modelling system), the analytical technique applied (steady-state, dynamic model, equilibrium model, etc.), the computational structure;
– Mechanisms addressed.

In this way, it would be possible to identify elements for combination/integration among methodologies and methods in the LCSA framework in a way that they complement each other and provide coherent, relevant, reliable and complete outputs.

4 Conclusions and outlook

The present study was aimed at depicting current debate on SS as a basis for identifying the main challenges for better mainstreaming sustainability within LCA-based approaches and LCSA, towards a comprehensive, transparent and robust approach to SA. In the first part of the study (Sala et al. 2012a), we focused on advancements in SS and SA methodologies, including an analysis of how life cycle-based methods are assessed against other approaches. In this paper, we have analysed the extent to which the principles of SS are embedded into LCSA and may contribute to further developing the frameworks.

In the current scientific development, both LCSA frameworks could prove their usefulness and robustness for a transparent and comprehensive SA. However, further improvements are necessary so that the ongoing developments of LCSA are in line with the most advanced SS ontological, epistemological and methodological concepts, attempting to bridge the gaps of the current methods for SA.

In Sala et al. (2012a), the crucial issues for SA methods entail: at ontological level, comprehensiveness, holism and system-wide approach; at epistemological level the shift from multi- towards inter- and transdisciplinarity, fostering the participation of stakeholders; and at methodological level, multi-scalability (geographical and temporal), in order to deal with complexity. Actually, a framework for SA should be able to better deal with externalities, interrelations, different applications, multiple stakeholder needs and multiplicity of legitimate perspectives of stakeholders, to deal with nonlinearities, normative choices, uncertainties and risks.

The two analysed LCSA frameworks are partially able to address the abovementioned issues. Moving from reductionism to holism, the LCSA (assessment) framework and ongoing activities combine several reductionist methodologies in order to cover more areas of investigation—in terms of topics related to SD, but still lack a more holistic approach to sustainability (in which also general system theory or complex system theory or post-normal science find a suitable role). Guinée et al. (2011) proposed a LCSA (analysis) framework that is more in line with the SS principles, as theoretically its core element is represented by the capability of addressing linkages and mechanisms, which are inherent characteristics of any SA.

Overall, LCSA should be developed in order to:

- Guarantee a holistic perspective in the assessment, with a strong sustainability orientation. It emerges from Sala et al. (2012a) and Gasparatos et al. (2008) that reductionism is still the dominant paradigm for SA. The holism implies the need to develop a robust framework for transdisciplinarity and the need to verify the comprehensiveness of the assessment (e.g. being able to assess the five capitals presented in part I).
- Be hierarchically different from LCA, eLCC and sLCA. It should represent the holistic approach integrating (and not substituting) the reductionist approach of the single part of the analysis. This implies maintaining the balance between analytical and descriptive approaches towards a goal- and solution-oriented decision support

methodology. This may benefit from convergence of endpoints among the pillars, in a conjunct effort towards environmental protection, human health protection and human well-being.

- Enhance transparency and scientific robustness.
- Tailor the assessment for local/specific impact (environmental, economic or social)
- Encourage and systematise the interaction among stakeholders involved in the development, application and use of the LCSA results (such as the scientific community, business associations and policy makers). The involvement should be at different levels: from values/vision sharing to data provision. Furthermore, also within the scientific community, there is a need to reinforce networking and exchange.
- Widen the goal of the integrated assessment. This should be shifted from avoiding negative impacts, to also proactively enhancing positive impacts, and then to do this in a manner that contributes to SD. This means that there is the urgency of incorporating sustainability goals within LCSA, moving from the comparative/analysis oriented to a much broader solution-oriented approach and scope

The challenging aim of LCSA, in the context of SS, is to promote social learning and mutual feedback (learning through doing and doing through learning) leading to co-production of knowledge with other stakeholder groups, such as businesses, politicians and society in a common process of problem identification and resolution.

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